An Expert System
for Screening Potentially Invasive Alien Plants
in South African Fynbos

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Table 2 Species list.

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Abbreviations: ? = unknown, DF = dry forest, GEN = generalist, GR = gravity, GTC = genetic, Hi = high, II = isolated individuals, Lo = low, LW = low woodland (functionally equivalent to dry forest for the expert), Med = medium, MDT = Mediterranean-type shrubland, N = no, OW = occasionally weedy, SP = specialist, VER = vertebrate, WAT = water, WDY = weedy, WND = wind, Y = yes.

Table 4 Paths for selected pines.
See Table 3 for abbreviations.
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Figure 3 Queries pertaining to population characteristics and habitat specialization (q6-q10 refer to questions 6-10 in Appendix 1)

Figure 4 Queries pertaining to seed dispersal (q11-q14 refer to questions 11-14 in Appendix 1)

Figure 5 Queries pertaining to seed production (q15-q19 refer to questions 15-19 in Appendix 1)

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ABSTRACT

The development and application of an expert system is described for screening alien plants for their invasive potential in South African fynbos. The system is proposed for mandatory use by potential introducers to demonstrate low invasive risk before importing exotic species for cultivation. Rules for the system were derived from empirical evidence by quantifying invasion windows and barriers that have limited the set of widespread invaders in fynbos to fewer than 20, out of several hundred introduced species. The system first compares broad-scale environmental conditions (climate and soils) between the home environment of a species and fynbos. Features of the plant in its home environment (basic life history traits, population characteristics, regeneration biology, habitat preferences) are then assessed. Finally, an assessment is made of life history adaptations to the prevailing fire regime in fynbos (juvenile period, fire-survival capacity of adult plants, seed bank longevity). The reasoning is explicit and the steps leading to a conclusion (high risk/low risk) can be retraced.

Besides the obvious application in identifying species with a high risk of invading, the system has considerable potential for modelling, and for teaching the concepts of biological invasions. The rules provide an explicit conceptualization of invasion processes and identify multiple paths to invasive success (not all of which have been realized yet). The system can therefore be used in planning control operations (i.e. for optimal allocation of control effort to critical stages in invasion), and for predicting the outcome of changes (e.g. in fynbos fire frequency) on the dimensions of invasion windows, and for assessing what changes are needed to prevent or reduce the extent of invasion by a given taxon.

Application of the system is demonstrated on a selection of Pinus, Banksia, and chaparral species.
INTRODUCTION

The spread of alien trees and shrubs is a major problem in fynbos, the natural vegetation of the southern and southwestern Cape Province of South Africa (Richardson et al. 1992). Dense stands of invasive trees and shrubs, notably species in the genera *Acacia, Hakea* and *Pinus*, alter many features of invaded ecosystems (Versfeld & van Wilgen 1986). They suppress indigenous plants, and currently threaten about 750 species with extinction. The alien stands have a much greater biomass and leaf area than fynbos and use more water, resulting in reduced stream flow from catchments. The altered vegetation structure sometimes leads to more frequent and more intense fires than in uninvaded fynbos (van Wilgen & Richardson 1985). Fires in dense alien stands are difficult to control and often have detrimental effects on the native biota. Alien plants also reduce the aesthetic value of fynbos. The control of existing dense stands of alien plants forms a major part of management action in mountain catchments and nature reserves in the fynbos (van Wilgen et al. 1992).

The most widespread invasive trees and shrubs in fynbos were introduced intentionally from mediterranean-climate regions on other continents to provide timber or fuel, for drift sand stabilization, or for aesthetic purposes. All the major woody invaders (Table 1) in fynbos were introduced to the region before 1870 and most have been widely planted (Richardson et al. 1992). Several hundred species introduced at about the same time and planted fairly extensively have not invaded or are much less widespread. Even within the genera *Hakea* and *Pinus*, which are well represented in the invasive flora, some species have failed to invade or are much less widespread than others. The differential success of introduced species as aliens provides a useful natural experiment for deriving empirical evidence on the factors that determine whether an introduced species will invade fynbos or not (Richardson & Cowling 1992). This can be used to derive procedures for determining, or at least ranking, the invasive potential of new arrivals (Richardson et al. 1990). New species are still being introduced for forestry, horticulture and other purposes, and effective screening will reduce the problem of invasive plants in the future.
Swarbrick (1991) stresses the need for a rating scheme for environmental weeds. Aggressiveness and potential impact are suggested as the dominant factors, and five classes of weeds are proposed. The most serious class, "canopy dominant", includes species capable of totally dominating the receiving community, replacing its canopy and altering its structure and functioning.

The other extreme is represented by "minor weeds" which do not dominate or significantly affect the target environment, and "ruderal" weeds which only invade recently disturbed areas and do not persist with the advance of more stable vegetation. The categories may be expanded to indicate life form, importance or other attributes using alphabetic suffixes. For example, *Pinus radiata* might be classified as *Itv* - a canopy dominant (class 1) tree (t) with visual impact (v) on the invaded community, etc. The concern here is with Swarbrick's first category, the most serious invaders of fynbos.

This paper describes the development and application of an expert system for screening alien plants to determine the risk of them invading fynbos and becoming canopy dominant weeds.
METHODS

Identification of barriers and invasion windows and the formulation of queries and rules

The expert system described here is an extension of the work by Richardson et al. (1990), Richardson and Cowling (1992) and Richardson et al. (1992). Using theoretical argument and empirical analyses, these authors developed a risk assessment model based on a biological profile of a successful invader and characteristics of the fynbos receiving environment. The processes involved in the invasion of fynbos by alien plants were conceptualized in the form of a flow diagram. The salient components that characterize potential barriers to an introduced plant, or, when conditions are beneficial, "invasion windows" (sensu Johnstone 1986), were thus identified. The original papers (op.cit) provide full details of the rationale for this approach.

The final flow diagram, the queries and the rules for the expert system were generated by repeatedly tracing the paths of known invaders through the "current" version and modifying it accordingly. At various stages of development, where possible, experts were informally consulted to comment on the system as whole and on certain aspects within their particular areas of expertise (e.g. soil chemistry, biological control).

Implementation

The expert system1 was developed using DmX, a development shell featuring exhaustive forward and backward chaining inference mechanisms and comprehensive truth-maintenance facilities (Decision Management Software, 1990). An explain facility is provided which enables users to query how the system reached a particular conclusion during the inference process. Inferences are implemented with MYCIN-like (Shortliffe 1976; Buchanan and Shortliffe 1984) backward-chaining (see Jackson 1990; Rich and Knight 1991). Search is strongly constrained to conform to the flow diagram (Figures 1 - 7). This was achieved by assigning suitable costs to the windows associated with the questions, and through use of the conventional procedural features of the language provided with the development shell.

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1A runtime version is available from the Institute of Plant Conservation, University of Cape Town, at a cost of R10 (US$10 for subscribers outside southern Africa) to cover handling costs, the disk and postage.
Using the expert system

The system was designed for use by ecologists with a good knowledge of fynbos and concepts of biological invasions. Some of the questions require knowledge of life history attributes of the species and characteristics of its home environment. The user is first required to enter the name of the species to be screened and to check fynbos default values for the typical fire return time, the minimum fire return time and the minimum annual rainfall. The system then queries the user to ascertain whether the species can be dismissed as low risk in terms of any of the invasion barriers. As soon as a classification is determined the system displays the result and allows the user to exit or ask for explanations.

Due to uncertainties inherent in the ecology of biological invasions (Richardson & Cowling 1992 and references therein), the system is explicitly conservative. A species is assigned high-risk status unless there is sufficient evidence that it has a very low likelihood of invading. Where applicable, if the user responds "unknown" to a question, that query is not taken into account, and control is transferred to the next module on the route to "high risk" status. Therefore, absence of information does not bias assessments towards "low risk" status.

Applications

The system was first used to show how the species that have already invaded fynbos overcame the various barriers to invasion and/or exploited invasion windows (i.e. which routes they have taken through the flow diagram). Assessments were also made of a range of exotic plant species which have not yet been introduced, or which have been introduced but have not yet shown signs of invading fynbos.
RESULTS

Identification of invasion windows and the formulation of queries and rules

The final flow diagram for assessing the risk of invasive success of introduced plants in fynbos comprised 24 questions (Appendix 1) which are grouped into six modules - the rectangles in Figure 1. The queries in these modules and the different routes to low and high risk status are shown in Figures 2 - 7. The standard output flowchart symbol is somewhat unconventionally used to mean "display risk status and either exit or explain depending on the next key pressed". Further background to the questions and implicit assumptions are given in Appendix 1. Details of the rules for assigning risk are presented in Appendix 2.

Applications

Introduced Species: current invaders and pines

By way of validation, the established invaders are all classified as high risk (HR1, Table 3) except for Acacia mearnsii, Paraserianthus lophantha and Pinus pinea. An empty cell in the table, or a value in square brackets, indicates that the system did not ask that question during the screening of that species. Most of the responses in Table 3 were based on information in Richardson et al. (1992). Responses for pines were derived from Richardson (1988), Richardson and Bond (1991), Richardson et al. (1990) and Richardson & Brown (1986). Primary sources for the Hakea responses were Richardson & Cowling (1992) and Kluge & Neser (1991). Molnar et al. (1989) contains useful information for Leptospermum laevigatum. B.B. Lamont (personal communication) provided most of the details for Hakea suaveolens. Stirton (1983) was also consulted in many cases.

Table 4 shows predicted paths for a collection of Pinus species, selected from Richardson et al. (1990), which have been introduced but have not yet invaded. All are assumed to be weedy in their home environments although an "unknown" response would lead to the same conclusion in every case. Most of the data contained in the table was gleaned from Richardson et al. (1990), Richardson & Bond (1991) and Richardson & Cowling (1992). Vertebrate dispersers in the home environments are assumed to be generalists (Question 12). Seeds are assumed to be structurally adapted for "long" wind dispersal if the seed-wing loadings, listed in Richardson et al. (1990), are
less than 50 (Question 14). The juvenile periods are minimum juvenile periods listed and referenced in Richardson et al. (1990). Provided a species is not excluded on criteria considered earlier, a juvenile period of less than 12 years (the fynbos default fire-return time) results in a high risk (HR1) classification. Fire survival capacity is "poor" if the fire tolerance index is 0 (thin bark), otherwise it is rated as "good" (Question 23) (cf. Richardson et al. 1990).

Potential Introductions

Richardson et al. (1990) identified Banksia (Proteaceae) as a genus with many species likely to be introduced on account of their commercial potential in the cut-flower market (Burgman and Hopper 1982). Predicted paths for a selection of Banksias previously assessed by Richardson et al. (1990) are shown in Table 5. Three of the Banksias listed in Table 5 have actually been introduced (Banksia coccinea, B. hookeriana and the shrub form of B. menziesii) (Richardson et al. 1990).

B.B. Lamont supplied responses for Banksia attenuata, B. burdettii, B. candolleana, B. hookeriana, B. laricina, B. leptophylla, B. menziesii and B. prionotes. The original responses given were not strictly adhered to as some of the questions were reworded as development of the system progressed. For the other Banksia species, information was derived from the data tabulated and referenced in Richardson et al. (1990).

Table 6 shows predicted paths for a selection of chaparral species, and a few other species of interest. Apart from Heteromeles arbutifolia, Rhus ovata, Rhamnus californica and R. croces, classified as high risk, the chaparral species were all classified as low risk (LR3). J.E. Keeley (personal communication) supplied responses for the chaparral species and B.B. Lamont (personal communication) for Grevillea leucopteris.
DISCUSSION

Identification of barriers and invasion windows and the formulation of queries and rules

The iterative process of developing the expert system elicited insights permitting extensions and refinements to the flowchart of Richardson and Cowling (1992). Extensions include more detailed consideration of the broadscale environmental conditions of the home environment (Figure 2), the role of biotic agents in determining habitat specificity for the "non-weedy" species (Figure 3) and dispersal vectors other than wind (Figure 4). The section concerning seed production has been refined to accommodate fynbos equivalents of biotic determinants of reproductive output which have a negative effect in the home environment (Figure 5).

Many of the underlying assumptions of the risk assessment model of Richardson and Cowling (1992) are retained by the expert system. Most of these are mentioned in Appendix 1 with the associated questions or are discussed below. Two implicit assumptions were called into question during analyses of pines and Banksias and deserve mention here. The first is that a species' attributes will not change after introduction. Some attributes used in risk assessment may vary across the range of a species, and change when the species is cultivated. For example, the juvenile period of Banksia candolliana may drop from 15 years in its natural environment to 5 years in cultivation; and Banksia leptophylla produces few seeds in cultivation (B.B. Lamont, personal communication). Species classified as "high risk" have by definition come from environments similar to fynbos and such effects are unlikely to be important in screening for environmental invasibility.

The second assumption concerns factors determining species distributions and other attributes in the home environment. In their analysis of pines, Richardson and Cowling (1992) concluded that factors restricting Pinus pinaster and P. halepensis to specific sites in the Mediterranean Basin do not operate in fynbos. Such conclusions are only possible after introduction and establishment, and the precise factors and subtle interactions involved are yet to be determined. For the purposes of the expert system, it is assumed, where necessary, that such factors will apply in fynbos.
Current Invaders Classified as Low Risk

*Acacia mearnsii* is classified as low risk (LR3, Table 3). Although fairly widespread in the biome (Richardson *et al.* 1992), it is dispersed by water and tends to be restricted to rivers, streams and ditches and is not a particular problem in the fynbos matrix. Nevertheless, it forms dense impenetrable stands, which suppress indigenous vegetation and reduce stream flow, and thus still adversely affects fynbos (Stirton 1983).

*Paraserianthus lophantha* is also water-dispersed but is dismissed as low risk (LR1i) after the first question (Question 1) as fire is not characteristic of the riparian habitats in which it occurs in its native western and southwestern Australia. However, like *Acacia mearnsii*, it does invade stream banks and seepages smothering rare indigenous native species and reducing stream flow (Stirton 1983).

*Pinus pinea* is classified as low risk (LR3) though it has invaded fynbos to a small extent on account of an opportunistic mutualism with the introduced grey squirrel, *Sciurus carolinensis*, which disperses its seeds (Richardson 1989). Invasions tend to be clustered around stands of the introduced tree, *Quercus robur*, whose acorns constitute the squirrel's principal food source (Millar, 1980). Such biological interactions may confound the predictions of the system. *Quercus robur*, incidentally, is classified as low risk (LR1i, Table 6) since intense fire is not characteristic of its riparian home environment (Question 1) (Knight 1985; Richardson 1989). It does, however, resprout after fires enabling it to persist in fynbos once established (cf. Question 23). Nevertheless, *Quercus robur* classifies as low risk on several counts. The seeds are water dispersed (LR3) and one can say, in retrospect, that seed predation by generalists in fynbos is high (LR4b).

The paths to high risk status taken by the other current invaders (Table 3) reflect the invasive functional groups and characteristics of a good invader described by Richardson and colleagues (Richardson *et al.* 1990, 1992; Richardson and Cowling 1992, 1993).
Introduced Species

Pines

Most of the pines considered have been introduced but have been planted on a very small scale, and have not escaped cultivation.

The invading pines (*Pinus halepensis*, *P. pinaster* and *P. radiata*) form a "fire-resilient" class (cf. McCune 1988). These are characterised by short juvenile periods, poor fire tolerance, they are strongly serotinous and have small seeds with adaptations for long distance dispersal by wind. In addition, they are not relegated to low risk status on any of the other criteria used by the system: the broad-scale environmental conditions of the home environments are similar to fynbos (Questions 1 - 4), they occur in similar vegetation types to those which occur within the fynbos biome (Question 5), they tend to be "weedy" in their home or naturalised environments (Question 6), relative to the home environment seed production is likely to be the same or higher in fynbos (Questions 15-19) and seed predation (Questions 20-21) is likely to be the same or lower. Operational definitions of terms like "high", "low" etc. are given in Appendix 1 alongside the questions where applicable.

Based on the above characteristics, the following pines are also classified as high risk species (HR1, Table 4): *Pinus attenuata*, *P. banksiana*, *P. clausa*, *P. contorta* var. *contorta*, *P. contorta* var. *latifolia*, *P. contorta* var. *murrayana*, *P. muricata*, *P. patula*, *P. pungens*, *P. serotina*, and *P. virginiana*.

In the absence of detailed information concerning many of the pines considered, the system was unable to classify "low risk" species, as previously identified by Richardson *et al.* (1990), as such. It did however distinguish them from the "high risk" pines, which were all classified as HR1, by classifying them as HR3 (*Pinus albicaulis*, *P. densiflora*, *P. gerardiana*, *P. koraiensis*, *P. lambertiana* and *P. sibirica*, Table 4). In order to clear these species for cultivation, more details of their reproductive output (Questions 15 - 19) and seed bank longevity (Question 24) will be required to demonstrate low risk. Note that HR3 is the least worrisome of the high risk categories. An HR3 species has a long juvenile period and poor fire tolerance. This means that if an individual germinates, it is unlikely to produce seeds before the next fire at which point it is killed. Persistence relies on its high reproductive output and long distance dispersal
abilities facilitating rapid recolonisation after fire (e.g. from cultivated stands, or areas where the fire return time has been longer than expected). The final question (Question 24) concerning seed bank longevity was answered "unknown" for all these HR3 species. Distinguishing pre- and post-dispersal longevity with varying seed release strategies remains an area for elaboration.

One point of departure from Richardson et al. (1990) lies in the handling of species dispersed by generalist vertebrates. Richardson et al. (1990) identified some species adapted for fire but 'restrained by the requirements for vertebrate dispersal' (e.g. Pinus flexilis and P. lambertiana). These were regarded as low risk species as generalist vertebrate dispersers are rare in fynbos. The tightness of mutualisms which may arise (cf. Redwing starlings and Acacia longifolia, below) are unpredictable, and the expert system does not automatically assign low risk to species dispersed by generalist vertebrate agents (cf. Pinus koraiensis, P. lambertiana, P. sibirica, P. strobus, Table 4). Note that this accords with the risk assessment model of Richardson and Cowling (1992).

The expert system is also more conservative in its classification of some of the group C (low risk) species of Richardson et al. (1990). Group C species possess combinations of traits associated with both high and low risk functional groups. Long juvenile periods are associated with low invasive risk. Where fire survival capacity is "good" the expert system assigns the species high risk status (HR2) provided its has not been excluded on any of the criteria investigated earlier (cf. Pinus balfouriana, P. canariensis and P. leiophylla).
Hakeas

The invading hakea species (*Hakea gibbosa*, *H. sericea*, and *H. suaveolens*) share many characteristics with the invading pines and have exploited similar invasion windows to achieve high risk status (HR1, Table 3). The differential invasive success within this genus has been largely attributed to differences in effective reproductive output which may be related to dispersal ability. *Hakea sericea* produces four and sixteen times as many seeds as do *H. gibbosa* and *H. suaveolens* respectively (Richardson *et al.* 1987). The prolific seed release of *H. sericea* has enabled it to colonise distant areas not colonised by the other two species (Richardson *et al.* 1992).

Another hakea, *Hakea salicifolia*, classified as high risk (HR1, Table 4), has been present in fynbos for more than 100 years but has not invaded. Although it produces large numbers of well dispersed seeds, these are inadequately insulated within the canopy follicles from fynbos fires (Richardson *et al.* 1987). The path suggests that it would be profitable to enhance the first module (Figure 2) to consider fire intensity. This issue has received most attention from the management perspective (references in van Wilgen *et al.* 1992). Techniques for pre-determining fire characteristics on the basis of environmental conditions have been developed but not successfully applied in fynbos (van Wilgen and Manders 1990). From the perspective of this exercise, fire represents an invasion barrier and it produces invasion windows. It is the chance nature of the event that is important. It was thus decided not to pursue the issue further and simply assumed that if fire is characteristic of the home environment, the species has the necessary adaptations to withstand fynbos fires (Question 1, Rule 23). Note that the lack of resolution in this module leads to a conservative high risk classification for a borderline case. Nevertheless, the system may require elaboration concerning fire intensity.
Acacias

The invading acacia species (Acacia cyclops, A. longifolia, A. melanoxylon and A. saligna) are also classified as high risk (HR1, Table 3), through a slightly different path to that followed by pines and hakeas. Differences in invasive success within this genus are largely attributable to reproductive output. Acacia saligna rapidly accumulates large seed banks in the soil. These are persistent due to high viability and water-impermeable dormancy. Seeds are dispersed primarily by ants but also (and further) by water. Rapid germination, cued by fire, accounts for its invasive success (Holmes 1989). Most of its seed crop is released soon after maturation.

Acacia cyclops also produces large seed banks though these are less persistent than those of A. saligna. The seeds are of variable viability and most do not survive a full year. Much of the seed crop is retained in the canopy for several months (O'Dowd and Gill, 1986). The seeds are dispersed by generalist vertebrates (birds) and are able to germinate without having to wait for specific disturbance cues. Thus, the two species invade fynbos using different strategies, taking alternative routes through the flowchart to high risk status (HR1).

Acacia longifolia achieves high risk status along the same path as Acacia cyclops. Although Acacia longifolia is not typically dispersed by birds, dispersal by Red-winged starlings (Onychognathus morio) has been a key factor in its success in mountain fynbos (Pieterse, 1986; Richardson et al. 1992). This is another example of an opportunistic mutualism which may confound predictions (cf. Pinus pinea & Sciurus carolinensis above).

Acacia melanoxylon, classified as high risk (HR1), possesses the characteristics required to invade fynbos but it only invades at forest edges and in riverine woodlands. The seeds are primarily dispersed by water and to some extent by birds. The assumption that birds disperse the seeds farther than does water to facilitate invasion results in this (conservative) high risk classification. The question of how much seed is dispersed by birds is not addressed. Long established "high risk" species which have not invaded may imply the existence of an unidentified barrier which the other invaders have overcome (e.g. post dispersal environments, dormancy and germination, cf. Keeley 1991).
Potential Introductions

Banksias

In accordance with the correspondence analysis of Richardson et al. (1990), the high risk species of Banksia (Table 5) reflect the functional groups identified. Note that the authors did not name functional groups for Banksias; the terms "non-invasive groups" and "invasive groups" are used here to indicate the two extremes along the gradient of invasive potential. The "invasive group" consists of tall, serotinous species which produce large numbers of well dispersed seeds and have short juvenile periods - attributes instrumental in the success of pines and hakeas (Lamont, Collins and Cowling 1985; Cowling, Lamont and Enright 1989; Enright and Lamont 1989b). The home environment of the Banksia species under consideration, southwestern Australia (Taylor and Hopper 1988), is similar to fynbos. The vegetation of the region is predominantly a fire-prone mediterranean-type shrubland or woodland with a fire return time varying between 10 and 20 years (Beard 1984) (Questions 1, 2 and 5). Soils are nutrient-poor (Question 3), and annual rainfall varies between 400 and 1000 mm (Milewski 1979; Lamont, Collins and Cowling 1985; Milewsky and Cowling 1985) (Question 4). For many of these Banksias, reproductive output is reduced by specialist insect seed predators (Scott 1982) which are generally not present in fynbos. Many species retain their seeds until cool, wet (winter) conditions arise suitable for germination and establishment (Cowling and Lamont 1985). This strategy, not found in fynbos proteaceae, minimises post dispersal seed predation irrespective of season of burn (Bond 1984; Cowling and Lamont 1987) (Questions 20-21).

Thus, thicket forming species which produce very large viable seed banks such as Banksia burdettii (Lamont and Barker 1988), B. hookeriana (Enright and Lamont 1989a) and B. leptophylla (Cowling et al. 1987) are classified as high risk (HR1) along with B. lacticina, B. prionotes, B. coccinea, B. media, B. meisneri var ascendens, B. meisneri var meisneri, B. quercifolia, B. scabrella, B. telmatiaea, B. victoriae and the non-sprouting form of B. violacea).
Richardson et al. (1990) note that many of these high-risk Banksia species (e.g. B. coccinea, B. hookeriana and B. prionotes) are highly susceptible to infection by the pathogenic fungus Phytophthora cinnamoni which attacks their root systems. The expert system does not address the influence of pathogens explicitly, though this effect is incorporated as a determinant of reproductive output by having a negative effect (Questions 15 - 19) or as effective seed predation (Questions 20 - 21). In this case the pathogen may (or may not) attack the root systems at any time rendering prediction of invasibility on this basis unreliable. The fungus is most destructive in plantations and it is not known whether it would be effective in controlling invasions by these species in fynbos.

The non-invasive functional group for Banksia spp. is characterised by low sprouting shrubs with low reproductive output (cf. Questions 15 - 19) and long juvenile periods (cf. Question 24) (Richardson et al. 1990). Examples include the widespread shrubs Banksia menziesii and B. attenuata (Cowling et al. 1987; Enright and Lamont 1989b), B. elegans which produces less than one seed per plant on average (Lamont and Barrett, 1988), and B. tricuspis which has a juvenile period of at least 20 years (Lamont and van Leeuwen 1988). All these species are classified as low risk (Table 5).

It should be noted that although the expert system reflects the functional groups of Richardson et al. (1990), it does not distinguish them. For example, species classified as HR1 do not necessarily fully correspond with the "fire resilient" functional group defined for pines or the "invasive group" for Banksias. "Fire-resilient" pines are killed by fire or at least have low fire tolerance. Fire tolerance is not considered in the path to HR1. The height of the plant is not considered by the expert system when classifying Banksias.
Chaparral Species

*Adenostoma fasciculatum, Arctostaphylos* spp. and *Ceanothus* spp. have refractory seeds (fire recruiters, Keeley 1991) which do not have specialised structures for long distance dispersal by wind. Question 11 asks for the principle dispersal vector. Where more than one is involved the user is asked to indicate the one which disperses farthest. *Arctostaphylos* seeds are not fleshy and not adapted for animal dispersal. However, Black bears and coyotes are known to eat the seeds occasionally (references in Keeley 1991) but are not regarded as seed predators or dispersal vectors for these species as they have no quantitative impact on the seed crop. Nevertheless, some seeds may pass through intact facilitating range expansion. This observation would lead to a high risk classification if one considers baboons (*e.g.* *Papio ursinus*) and/or rodents as equivalent generalist dispersal vectors in fynbos. This route is the path to high risk taken by *Heteromeles arbutifolia, Rhus ovata, Rhamnus californica* and *Rhamnus croceus* (Table 6) which are adapted for dispersal by generalist vertebrates (Keeley 1991).

Comparison with other approaches

Various models and rating systems for screening exotic species and predicting pest status have been proposed during the last decade and a half (*e.g.* Weir 1977; Arthington and Mitchell 1986; Navarantham and Catley 1986; Smallwood and Salmon 1992; Scott and Panetta 1993). Apart from Navarantham and Catley (1986), most of the earlier models lack quantification and the resolution required for use in prioritising exotic species in terms of pest potential (Smallwood and Salmon 1992).

More recently, Scott and Panetta (1993) developed a method of predicting weed status for southern African plants introduced to Australia. Statistical techniques (multiple logistic regressions) revealed that problem species are typically widespread, "weedy", are found in a range of climates in southern Africa, and have been established in Australia for a long time (longer than 140 years for the best fitting regressions). For agricultural weeds, existence of congeneric weeds in southern Africa and climatic range (taken together), and the single variable "weed status in southern Africa", were found to be good predictors of weed status in Australia. No suitable predictors of weed status for non-agricultural (environmental) weeds were found.
Smallwood and Salmon (1992), using exotic bird and mammal pests with well known invasion histories, developed a rating system to prioritise research and control of established problem alien organisms. They used four additive criteria: potential to be introduced, to establish, to cause damage and to be controlled. Their concern is broader than the screening of intentionally introduced species, extending to accidental introductions and prioritisation of candidate species. Furthermore, the authors claim that the approach is easily adapted for use anywhere. Modifications would centre around 'location-specific concerns for natural areas, resources, agricultural production systems, and human health' (Smallwood and Salmon 1992) - i.e. human concerns rather than characteristics of organisms and receiving environments.

The system, described here, focuses on specific interactions between the fynbos receiving environment and characteristics of species likely to be introduced. Although, on the surface, the questions and rules may seem to be applicable to all mediterranean-type shrublands as receiving environments, claims of such generality are premature. The barriers and windows will definitely be different in dissimilar environments. The approach, however, can certainly be applied elsewhere - a simple expert system providing practical "rules of thumb" using information directly pertaining to the biology of the organisms involved and characteristics of the receiving environment. The prerequisite is considerable insight into the relevant ecological interactions and processes for successful development of the expert system. The other two approaches are removed from the biological mechanisms of the invasion process.

Scott and Panetta (1993) are aware of this problem in their "sociological" approach and suggest that it may account for their finding relationships for agricultural weeds and not for environmental weeds; agricultural weeds are more closely associated with human activities.

An obvious confounding case for methods using (or based on) weediness (or pest status) in the home environment as a predictor of the same elsewhere is a species whose reproductive output is suppressed by biotic agents in the home environment. Ecological release in the target environment results in weediness (or pest status) which is not characteristic of the home environment. Scott and Panetta (1993) examined residuals in their analysis of South African weeds in Australia and identified two important species in this category: Mesembrianthemum crystallinum L. (Aizoaceae) and Watsonia meriana (L.) Mill. (Iridaceae). They further suggest
that such species may be 'good candidates for biological control' and advocate a similar analysis for the identification of biocontrol agents. The assumption is that common and widespread insects establish more readily (Crawley 1987). The process would clearly need to be taken further - towards the level of biological interactions - investigating, for example, whether the species is a specialist seed predator (cf. Questions 20-21) and is safe to introduce.

Regarding prioritisation, ranking of species has not been an objective of this study, but, provisionally, the following order of invasive potential for the classifications is suggested:

LR1i < LRii < LRiii < ... < LR5 < HR3 < HR2 < HR1. Differential invasive success within genera, or species exploiting similar invasion windows, due to differences in reproductive output, for example, could add to the resolution within the class LR4. The relationship is complicated by the fact that for many species, more than one barrier may apply (cf. *Quercus robur* above). Untangling the complexities of combinations of strategies renders the problem of ranking intractable. For practical purposes, the two categories "low risk" and "high risk" suffice.

Along with other factors, the length of time since introduction has been associated with weed status (e.g. Scott and Panetta 1993). One interpretation of this observation relates to the fact that an invasion window may "open" as a result of an unusually long dry season or short fire interval facilitating establishment. Once established the species might generate very large numbers of persistent seeds enabling it to continue to proliferate in conditions where it was unable to establish. Crawley (1989) discusses the interaction of chance events and timing in determining community structures. Noble and Slatyer (1980) give further examples illustrating dramatic differences in resulting community structure depending on the timing of an event. The longer an alien organism resides in an area (in cultivation for example), the more likely it will encounter conditions suitable for establishment (outside of cultivation). Therefore, use of mean and expected values for attributes of the receiving environment and species attributes are not sufficient for predicting invasive success. Maxima and minima (e.g. minimum fire return time, maximum seed bank longevity, etc.) may be of more significance when heuristically combined with experience of the invasion process (cf. Ralls and Starfield, subm.).

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Advantages of the expert systems approach

The logic behind the system can be conceptualised as a decision tree (evident from the flow diagrams, Figures 1 - 7). Decision trees provide a straightforward method of reaching a decision, but the flowcharts tend to be too cryptic and awkward when referring to supplementary notes for more complete explanations of the requirements of particular questions. Where necessary, the expert system provides as much as a full screen of supportive information, and more if required.

In addition, the usual benefits of expert systems apply. A formalised and automated inference mechanism underlies the reasoning, eliminating human error in this facet. One of the most important advantages is transparency. The system’s reasoning is easily followed both during the session, through the help facilities, and after a species has been classified, through the explain feature. The explain feature provides a detailed explanation for the system’s classification and the user may justify a final decision by accepting or rejecting the system’s conclusions at any point in the path to a decision. Expert systems excel in situations where reasoning with incomplete or uncertain data is necessary. This is always the case in ecology where true replication does not occur, data sets are never "complete" and decisions have to be made nevertheless. The expert system described here does not explicitly deal with uncertainty. Confidence in the system’s conclusions is set by the extent to which users accept the underlying assumptions of the rules.

Crawley (1987) argues that we may 'never be able to predict which of a set of invaders is likely to establish, and which, having become established, is likely to become the most abundant'. Similarly, Ehrlich (1989) states that we cannot predict the outcome of a particular introduction. These statements are certainly true as far as generalised approaches are concerned, but by starting from scratch with the mechanisms of the invasion process, identifying the barriers that need to be overcome and the invasion windows to be exploited in the receiving environment, and then examining attributes of the species of interest, one can go a long way towards assessing the risk of invasion by that species in the particular environment. At the very least species with low invasive risk can be identified.
Immediate Uses

In the absence of strict legislation and control on the importation of alien plants (cf. Glavovic 1993), the system was developed for academics to make the point that some form of prediction is possible, and that risk assessment may be achieved relatively simply for improved decision making. As it stands, the system can be used to assess the invasive risk associated with the introduction of particular woody trees and shrubs - species which fall into Swarbrick's (1991) "canopy dominant weeds" category. If one intends to introduce a species for commercial reasons and does not have all the information the system requires, a high risk classification will result. By recording unknown responses the user can then identify the specific information to obtain or areas for research. The system also has potential for modelling and other types of scenario testing by experimenting with the fynbos defaults set at the start of a session. These may change in the face of global warming. For example, fire frequency may increase causing some high risk species with juvenile periods close to the current fire return time to become low risk.

Another potential application is for teaching the concepts of biological invasions. Developing an expert system is a useful educational exercise in itself. The principle benefit is in learning to synthesize information (Starfield and Bleloch 1991). Reasoning is necessarily explicit and consistent. Both inferential and factual knowledge are accessible. Furthermore, experimenting with the finished expert system and exploring the information contained in help screens and hypertext attachments can also be very informative.

Applications beyond the simple screening of canopy dominant species are stretching the original purpose of the system. Primarily this paper responds to the need for a screening system and suggests that a system like this should be used before approving any introductions. Rather than conservationists having to identify "noxious weeds", horticulturalists intending to introduce an alien plant for cultivation should be required, in advance, to demonstrate low risk of invasion using a system acceptable to conservationists.
Future Developments

The system could be expanded to categorise (in terms of Swarbrick's classes) the species to be introduced, and then screen accordingly. At present, in excess of 50% of the budget for conserving the Cape mountain catchments is allocated to alien control (Richardson and Cowling 1993). Most of this is used for control of the most serious invaders (canopy dominant weeds). It may be some time before due attention can be paid to the less serious invaders.

In view of the limited user base at present, the user interface and help facilities including a hypertext attachment for background information have not been fully developed and evaluated. In future, these aspects could prove invaluable as the user base extends to a broader range of horticulturalists and nature conservancies. In the current version the system is clearly very responsive at each level. It simply outputs a result and exits if low risk is indicated, or proceeds to an independent module. Future versions will require comprehensive sensitivity analyses and tests of robustness.

The underlying knowledge of this system may become an integral part of an expert system for prioritising and designing control strategies for established invaders. Control measures can be directed towards critical stages in the invasion process. For example, if reproductive output is very high, seed attacking biocontrol agents should be considered. The existence of a suitable specialist seed predator could reduce the level of risk associated with a species. As a decision support tool in this context, the system may be supplemented with hypertext and modelling components for ready access to relevant background information. The modelling component could consist of simple individual-based models (cf. DeAngelis & Gross 1992) using cellular automata (see McGlade 1993 for background information and Colasanti & Grime 1993 for a relevant example) to graphically illustrate relative rates of alien spread given various parameters (e.g. juvenile period, number of seeds produced, seed-wing loading, prevailing wind velocity etc.).
CONCLUSIONS

The expert systems approach shows great promise in the area of decision support for the screening of potentially invasive plants in fynbos. The development cycle can yield valuable insights into specific mechanisms of invasion and the finished product comprises a defendable component of the decision process. An expert system can draw attention to the factors to be considered when assessing the invasive risk of a species and indicate areas for further investigation/research.

In contrast to the more standard statistical or "sociological" approaches (e.g. Scott and Panetta 1993), this approach is close to the biology of the specific classes of organisms involved and their likely interactions with the target environment. This is a move away from generalised mathematical models, predicting average or expected behaviours, towards the level of specific ecological interactions. When developing heuristics for this type of risk assessment, the extremes, rather than average behaviours, are often of more significance. The system is designed to enable anyone, who intends to introduce a woody tree or shrub into the fynbos biome for cultivation, to screen the plant and indicate why the species is not likely to invade, if that is indeed the case; otherwise a high risk classification will result. Provided the heuristics are approved by conservationists, this procedure should be mandatory, in advance of any introductions, at the introducer's expense. Shifting the responsibility onto the developers obviates the need for conservationists to identify open ended sets of "noxious weeds".

The expert systems approach does not aspire towards a generalised theory of the invasion process. The aim is to produce a set of practical heuristics for better, defendable real-world decisions, in the absence of valid theory and complete data.
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REFERENCES


Appendix 1 Questions and associated rationale for assessment of the risk of invasive success of introduced plants in fynbos.

1. Is intense fire a prominent characteristic of the home environment and does the area have a fire-adapted biota? (yes/no). It is assumed that only species from fire-prone systems will invade fynbos (Rule 18).

2. What is the typical fire return time (in years) in the home environment (enter 40 if unknown)? (enter a number between 0 and 40)

3. With respect to total N and P in the soil, is the home environment nutrient-poor? (yes/no/unknown)
   Nutrient-poor soils are those with total soil nitrogen and phosphorus contents of < 0.3% and < 0.06% respectively. These values characterise the soils of mediterranean-type ecosystems in Australia, California and the Mediterranean Basin (the source of all the invasive taxa listed in Table 1).

4. What is the annual rainfall in the home environment (mm)? (enter a number). It is assumed that a species will not invade unless the annual rainfall in the home environment is at least as much as the minimum annual rainfall in fynbos (Rule 1). The default value is 400mm. No species from areas with lower rainfall have invaded fynbos.

5. In what type of vegetation does the species occur in its home range? (mediterranean-type shrubland, dry forest, wet forest, savanna). Only species occurring in mediterranean-type shrubland or dry forest are deemed worthy of further investigation. No wet forest and savanna species have been known to invade fynbos.
6. In its home environment the species typically occurs as ____? (isolated individuals / isolated individuals but occasionally thicket-forming or 'weedy' / a thicket-forming or 'weedy' species). Habitat specific species which occur as isolated individuals in a habitat restricted in fynbos are dismissed as low risk (Rule 9).

7. In its home environment, is the species obviously a habitat specialist? (yes/no)
   For example, is it restricted to riparian zones or to a particular soil type with restricted distribution. The habitat restriction may be abiotically (e.g. soil nutrient characteristics) or biotically determined. If biotically determined, equivalent biotic agents must be present in fynbos for successful invasion.

8. The species has been identified as a habitat specialist. Is this habitat specialisation biotically determined? (yes/no/unknown)

9. Is it likely that any biotic agents will have the same effect in fynbos? (yes/no)

10. Is this habitat restricted in fynbos? (yes/no)

   The ability to disperse over fairly "long" (see Question 14) distances adds to the invasive risk associated with a species.

   In general, species whose seeds are dispersed by water, invertebrate animals (e.g. ants) or gravity do not invade fynbos. Species whose seeds are dispersed over long distances by vertebrate animals (e.g. birds) and wind, however, stand a better chance of invading. In the case of vertebrate animals, the system asks whether the dispersal agent is a generalist or specialist (in the home environment). If specialist, and there is no equivalent in fynbos, the species is classified as low risk (Rule 11). Otherwise the system continues with questions concerning seed production (Question 15).
11. What is the principle dispersal vector? (water/ invertebrate animal(s) / gravity / vertebrate animal(s) / wind)

If the species exhibits more than one mode of dispersal, select the one which disperses furthest. For example, Acacia longifolia is dispersed by ants and birds, but vertebrate animals (birds) disperse seeds further than do ants, and are more important for widespread invasion.

12. The seeds are dispersed by vertebrate animals. Does the species require a specialist dispersal vector? (specialist/generalist)

13. Is there an equivalent dispersal vector in fynbos? (yes/no)

14. Does the seed have adaptations, such as a low seed-wing loading, for dispersal over long distances by wind? (yes/no)

"Long distance" means that dispersal over several hundred metres is common. Short distance means that seeds are seldom dispersed further than 100 metres.

A species may be dismissed as low risk if its cumulative seed production between fires is low. Even if low in the home environment, the system investigates the effects of biotic determinants of reproductive output. If a biotic determinant of reproductive output has a positive effect in the home environment and is not present in fynbos (and there is no analogue), the species is classified as low risk (Rule 14). If a biotic determinant of reproductive output has a negative effect in the home environment and the organism (or an analogue) is present in fynbos, the species is dismissed as low risk. Otherwise, seed production is assumed to be high and seed predation is considered which, if high, may reduce the risk of invasion associated with the species.
15. In its home environment, the annual seed production (number of plump seeds produced per plant) is ____? (low/medium/high) (0-50, 50-500, > 500 respectively; see Richardson et al. 1990 for discussion).

For serotinous plants or any species with a seed bank (in the canopy or soil) this refers to the cumulative seed production, i.e. the seed bank at the average fire return interval for the target environment (12 years for fynbos).

16. The determinant of reproductive output is ____? (biotic/genetic/unknown)

17. Does the biotic determinant of reproductive output have a positive effect? (yes/no)

18. Seed production is low, reproductive output is biotically determined. Is the determinant of reproductive output present in fynbos? (yes/no)

19. Is there an equivalent determinant of reproductive output in fynbos? (yes/no)

It is assumed that equivalent (or the same) biotic agents in fynbos will have the same effect as they do in the home environment. Crawley (1987) describes an example which throws doubt on this assumption: the gall forming cynipid wasp, Andricus quercusitalicis, and Quercus robur in the U.K. If seed predation is likely to be high in fynbos (relative to the home environment) and if seed predation in the home environment is largely by generalists, the species is classified as low risk (Rule 16). Otherwise, life history adaptations to the type of fires characteristic of fynbos are considered as the final filter (Questions 22-24).
20. Pre- and post- dispersal seed predation. Relative to the home environment, seed predation in fynbos is likely to be ____? (higher/ lower/ the same/ unknown)

For example, if the species has special seed protection structures such as follicles that exclude all but specialised seed predators (that are not introduced simultaneously) then pre-dispersal seed predation in fynbos will probably be low.

21. Is the seed predator a specialist? (yes/no/unknown)

i.e. In the home environment is the majority of the net seed loss (pre- and post- dispersal) attributable to biotic agents caused by specialist animals, or by a range of generalists?

The highest risk is posed by species which have not been excluded on any of the preceding criteria and are capable of producing viable seeds within a single fynbos fire cycle (Rule 3).

Species with longer juvenile periods but able to withstand the intense fires characteristic of fynbos constitute the next highest risk category (Rule 4).

The final high risk category is for species with a longer juvenile period than the typical fynbos fire interval, a poor fire survival capacity but whose seed banks persist for longer than the typical fire return time in fynbos (Rule 5).

22. The juvenile period of the species is ____ years. (enter number) At what age is mature seed available for re-establishment, or how long after fire/germination does the species produce viable seed (minimum time)?

23. The fire survival capacity of adult plants is ____? (good/poor)

24. The seed bank longevity is _____ (in years)? (enter number) How long do seeds in the seed bank remain viable?
Appendix 2 Rules for the allocation of risk status to introduced plants in fynbos.

1. IF
   Fynbos_Min_Annual_Rainfall < HomeEnvironment_Annual_Rainfall
   THEN
       Annual_Rainfall_Similar  
       {i.e. fynbos rainfall acceptable}

2. IF
   NOT LR AND  
   (HR1 OR HR2 OR HR3)
   THEN
       HR
       {high risk}

3. IF
   NOT LR AND  
   Juvenile_Period_Short = 1
   THEN
       HR1
       {high risk 1}

4. IF
   NOT LR AND  
   Juvenile_Period_Short = 0 AND  
   Fire_Survival_Capacity = 1
   THEN
       HR2
       {high risk 2}

5. IF
   NOT LR AND  
   Juvenile_Period_Short < 0.5 AND  
   Fire_Survival_Capacity = 0 AND  
   Seed_Bank_Longevity > 0.5
   THEN
       HR3
       {high risk 3}

6. IF
   Fynbos_Typical_Fire_Return_Time > Juvenile_Period
   THEN
       Juvenile_Period_Short

7. IF
   LRi OR LRii OR LRiii OR LRiv OR LR1 OR LR2 OR LR2b OR  
   LR3 OR LR4 OR LR4a OR LR4b OR LR5
   THEN
       LR
       {low risk}

8. IF
   HomeEnvironment > 1  
   THEN
       LR1
       {low risk 1 - home environment risk}
9. IF 
NOT LR1 AND 
Population_Characteristics = 0 AND 
Habitat_Specialist = 0 AND 
(Habitat_Specialisation_Biotically_Determined = 0 OR 
Habitat_Specialisation_Biotically_Determined = 1 AND 
Equivalent_Biotic_Agents_in_Fynbos = 0) AND 
Habitat_Restricted_in_Fynbos = 0 OR 
LR2b 
THEN 
LR2 
{low risk - habitat specialisation}

10. IF 
Population_Characteristics = 0 AND 
Habitat_Specialist = 0 AND 
Habitat_Specialisation_Biotically_Determined = 1 AND 
Equivalent_Biotic_Agents_in_Fynbos = 1 
THEN 
LR2b 
{due to biotically determined habitat specialisation, risk is low}

11. IF 
NOT LR2 AND 
Principle_Dispersal_Vector = 3 AND 
Dispersal_Vector_Specificity = 0 AND 
Equivalent_Dispersal_Vector_In_Fynbos = 0 OR 
LR3a OR 
LR3b 
THEN 
LR3 (dispersal risk is low)

12. IF 
NOT LR2 AND 
Principle_Dispersal_Vector = 0, 1 or 2 
THEN 
LR3a 
{low risk}

13. IF 
NOT LR2 AND 
Principle_Dispersal_Vector = 4 AND 
Inherent_Seed_Dispersability = 0 
THEN 
LR3b 
{low risk}

14. IF 
NOT LR3 AND 
Annual_Seed_Production = 0 AND 
Determinant_of_Reproductive_Output = 0 OR 
Annual_Seed_Production = 0 AND 
Determinant_of_Reproductive_Output = 1 AND 
Positive_Effect = 0 AND 
Organism_Present_in_Fynbos = 0 AND 
Equivalent_Determinant_of_Reproductive_Output = 1 
THEN 
LR4 
{genetic reproductive output risk is low}
15. IF NOT LR4 AND  
  Annual_Seed_Production = 0 AND  
  Determinant_of_Reproductive_Output = 1 AND  
  Positive_Effect = 1 AND  
  (Organism_Present_in_Fynbos = 1 OR  
   Organism_Present_in_Fynbos = 0 AND  
   Equivalent_Determinant_of_Reproductive_Output = 0)  
  THEN  
  LR4a  
  {biotic reproductive output risk is low}  

16. IF NOT LR4a AND  
  Seed_Predation = 0 AND  
  Specialist_Predator = 0  
  THEN  
  LR4b  
  {risk, reduced by seed predation, is low}  

17. IF NOT LR4b AND  
  Juvenile_Period_Short < 0.5 AND  
  Fire_Survival_Capacity = 0 AND  
  Seed_Bank_Longevity_Long < 0.5  
  THEN  
  LR5  
  {juvenile period long, fire survival poor, seedbank short-lived - risk low}  

18. IF Fire_Characteristic_of_Home_Environment = 0  
  THEN  
  LRi  
  {intense fires are not prominent in the home environment: low risk}  

19. IF Similar_Fires < 0.5  
  THEN  
  LRii  
  {risk due to fire similarity is low}  

20. IF Similar_Nutrients = 0  
  THEN  
  LRiii  
  {risk, due to dissimilar soil nutrient characteristics, is low}  

21. IF NOT Annual_Rainfall_Similar  
  THEN  
  LRiv  
  {risk, due to dissimilar rainfall is low}  

22. IF Seed_Bank_Longevity > Fynbos_Min_Fire_Return_Time  
  THEN  
  Seed_Bank_Longevity_Long  

23. IF Fire_Characteristic_of_Home_Environment AND  
  Home_Environment_Fire_Return_Time > Fynbos_Min_Fire_Return_Time  
  THEN  
  Similar_Fires
Figure 1  Modules of the expert system for assessing the invasive potential of introduced plants in South African fynbos. Details of the queries within each module are given in Appendix 1.
Figure 2 Queries pertaining to broad-scale environmental conditions.

(q1 - q5 refer to Questions 1-5 in Appendix 1)
Figure 3  Queries pertaining to populations characteristics and habitat specialisation (q6 - q10 refer to Questions 6 - 10 in Appendix 1)
Figure 4  Queries pertaining to seed dispersal (q11 - q14 refer to Questions 11 - 14 in Appendix 1)
Figure 5  Queries pertaining to seed production (q15 - q19 refer to questions 15 - 19 in Appendix 1)
Figure 6 Queries pertaining to seed predation (q20 - q21 refer to Questions 20 - 21 in Appendix 1)

Figure 7 Queries pertaining to life history adaptations to fynbos fire (q22 - q24 refer to Questions 22 - 24 in Appendix 1)
Table 1  Widespread alien plants in fynbos (after Richardson et al. 1992). Extent of invasion is expressed as the percentage of the 198 quarter degree squares in the fynbos biome.

<table>
<thead>
<tr>
<th>No</th>
<th>Species</th>
<th>Family</th>
<th>Origin</th>
<th>Extent of invasion</th>
<th>Date introduce</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Acacia cyclops</em></td>
<td>Fabaceae</td>
<td>Australia</td>
<td>65</td>
<td>1857</td>
</tr>
<tr>
<td>2</td>
<td><em>Acacia longifolia</em></td>
<td>Fabaceae</td>
<td>Australia</td>
<td>42</td>
<td>1827</td>
</tr>
<tr>
<td>3</td>
<td><em>Acacia mearnsii</em></td>
<td>Fabaceae</td>
<td>Australia</td>
<td>47</td>
<td>1858</td>
</tr>
<tr>
<td>4</td>
<td><em>Acacia melanoxylon</em></td>
<td>Fabaceae</td>
<td>Australia</td>
<td>26</td>
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Table 3. Current invaders and their paths to high risk status.
Species numbers correspond with Table 1.
Abbreviations: ? = unknown, DF = dry forest, GEN = generalist, GR = gravity, GTC = genetic, Hi = high,
II = isolated individuals, Lo = low, LW = low woodland (assumed equivalent to dry forest by the expert system),
MED = medium, MDT = Mediterranean-type shrubland, N = no, OW = occasionally weedy, SP = specialist,
VER = vertebrate, WAT = water, WDY = weedy, Y - yes

| SPECIES NUMBERS | QUESTION NUMBERS | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | Outc |
|-----------------|------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|    |
| 1               |                  | Y  | ?  | Y  | ?  | MED | WDY|    |    |    |    |    |    |    |    |    | VER | GEN | Hi  | Hi  | both | 3  |    |    |    |    |    |    |    |    |
| 2               |                  | Y  | ?  | Y  | ?  | DF  | WDY|    |    |    |    |    |    |    |    |    |    |    |    |    |    | Hi  | both | 3  |    |    |    |    |    |    |    |    |
| 3               |                  | Y  | ?  | Y  | ?  | DF  | WDY|    |    |    |    |    |    |    |    |    |    |    |    |    |    | WAT |    |    |    |    |    |    |    |    |
| 4               |                  | Y  | ?  | Y  | ?  | 800 | DF  | WDY|    |    |    |    |    |    |    |    |    | VER | GEN | Hi  |    |    |    |    |    |    |    |    |    |
| 5               |                  | Y  | ?  | Y  | ?  | MED | WDY|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    | VER | Hi  | both | 3  |    |    |    |    |    |    |    |
| 6               |                  | Y  | 15 | 20 | 800 | DF  | II | N  |    | WND | Y  | MED |    |    |    |    | Lo  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 7               |                  | Y  | 15 | 20 | 800 | DF  | OW |    | WND | Y  | Hi  |    |    |    |    | Lo  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 8               |                  | Y  | ?  | Y  | ?  | 650 | MED | WDY|    | WND | Y  | MED |    |    |    |    | Lo  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 9               |                  | Y  | ?  | Y  | ?  | 725 | MED | WDY|    | WND | Y  | Hi  |    |    |    |    | Lo  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 10              |                  | N   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 11              |                  | Y  | 15 | Y  | 600 | DF  | WDY|    | WND | Y  | Hi  |    |    |    |    | Lo  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 12              |                  | Y  | 15 | Y  | 500 | DF  | WDY|    | WND | Y  | Hi  |    |    |    |    | Lo  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 13              |                  | Y  | 15 | Y  | 700 | DF  | OW |    | VER | SP | N  | [Hi] |    | [Lo] | [15]| [Poor]| [short] | LR3 |
| 14              |                  | Y  | 15 | Y  | 600 | DF  | WDY|    | WND | Y  | Hi  |    |    |    |    | Lo  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 15              |                  | N   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
Table 4. Paths for selected pines.
See Table 3 for abbreviations.

| Pinus taxon | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | RISK |
|------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|     |
| albicaulis | Y | ? | Y | ? | DF | WDY | VER | GEN | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 20 | Poor | ?   | HR3 |
| aristata   | Y | ? | Y | ? | DF | WDY | WND | Y  | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 20 | Good | HR2 |
| attenuata  | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  5 | HR1  |
| balfouriana| Y | ? | Y | ? | DF | WDY | WND | Y  | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 20 | Good | HR2 |
| banksiana  | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  3 | HR1  |
| canariensis| Y | ? | Y | ? | DF | WDY | WND | Y  | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 15 | Good | HR2 |
| clausa     | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  5 |       | HR1 |
| contorta-c | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  4 | HR1  |
| contorta-l | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  5 | HR1  |
| contorta-m | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  6 | HR1  |
| densiflora | Y | ? | Y | ? | DF | WDY | WND | Y  | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 20 | Poor | ?   | HR3 |
| flexilis   | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo | 28 |       | HR2 |
| gerardiana | Y | ? | Y | ? | DF | WDY | WND | Y  | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 20 |       | HR2 |
| koraiensis | Y | ? | Y | ? | DF | WDY | WND | Y  | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 15 |       | HR3 |
| lambertiana| Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo | 40 |       | HR2 |
| leiophylla | Y | ? | Y | ? | DF | WDY | WND | Y  | ?  |     |     |     |     |     |     |     |     |     |     |     | Lo | 28 |       | HR2 |
| muricata   | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  5 |       | HR1 |
| patula     | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo | 10 |       | HR1 |
| pungens    | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  5 |       | HR1 |
| serotina   | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  4 |       | HR1 |
| strobus    | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  5 |       | HR1 |
| virginiana | Y | ? | Y | ? | DF | WDY | WND | Y  | Hi |     |     |     |     |     |     |     |     |     |     |     | Lo |  5 |       | HR1 |
Table 5. Paths for selected Banksias.
See Table 3 for abbreviations.

| Banksia taxon | 1 | 2  | 3   | 4     | 5     | 6     | 7   | 8     | 9     | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | RISK |
|--------------|---|----|-----|-------|-------|-------|-----|-------|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| attenuata    | Y | 10-20 | Y | 450-1000 | MDT,DF | WDY | [Y] | [N] | WND | Y | Lo | GTC | [SP] | 20 | [Good] | 15 | LR4 |
| burdettii    | Y | 10-20 | Y | 550 | MDT | OW | [Y] | [N] | WND | Y | Med | Lo | [SP] | 5 | [Poor] | 10 | HR1 |
| candolleana  | Y | 10-20 | Y | 500 | MDT | WDY | [Y] | [N] | WND | Y | Lo | GTC | [SP] | 15 | [Good] | 15 | LR4 |
| coccinea     | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 1-5 | HR1 |
| elegans      | Y | 10-20 | Y | 400-1000 | MDT | ? | WND | ? | Lo | GTC | [SP] | 6 | HR4 |
| hookeriana   | Y | 10-20 | Y | 500 | MDT | WDY | [Y] | [N] | WND | Y | Med | [GTC] | Lo | 5 | [Poor] | 10 | HR1 |
| laricina     | Y | 10-20 | Y | 600 | LW | OW | [Y] | [N] | WND | Y | Med | [GTC] | Lo | 5 | [Poor] | 10 | HR1 |
| leptophylla  | Y | 10-20 | Y | 450-650 | MDT, LW | WDY | [Y] | [N] | WND | Y | Med | [GTC] | Lo | 5 | [Poor] | 15 | HR1 |
| media        | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 5-10 | HR1 |
| meisneri-a   | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 5-10 | HR1 |
| meisneri-m   | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 5-10 | HR1 |
| menziesii    | Y | 10-20 | Y | 450-1000 | MDT, DF | II | Y | N | ? | Y | Lo | GTC | [SP] | 20 | [Good] | 5 | LR4 |
| prionotes    | Y | 10-20 | Y | 450-1000 | MDT, LW | WDY | [Y] | [N] | WND | Y | Med | [GTC] | [SP] | 5 | [Poor] | 10 | HR1 |
| guercifolia  | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 5-10 | HR1 |
| scabrella    | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 1-5 | HR1 |
| telmatiaea   | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 1-5 | HR1 |
| tricuspis    | Y | 10-20 | Y | 400-1000 | MDT | ? | WND | Y | Lo | GTC | [SP] | 20 | HR4 |
| victoriae    | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 1-5 | HR1 |
| violacea-n   | Y | 10-20 | Y | 400-1000 | MDT | WDY | WND | Y | Hi | Lo | 1-5 | HR1 |
Table 6. Paths for selected chaparral and other species of interest.
See Table 3 for abbreviations.

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